The flavor-changing rare top decays $t \rightarrow cVV$ in topcolor-assisted technicolor theory

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Abstract

In the framework of topcolor-assisted technicolor (TC2) theory, we calculate the contributions of the scalars(the neutral top-pion π_t^0 and the top-Higgs h_t^0) to the flavor-changing rare top decays $t \rightarrow cVV(V = W, g,\ \gamma$ or $Z)$. Our results show that h_t^0 can enhance the standard model $B_r^{SM}(t \longrightarrow cWW)$ by several orders of magnitude for most of the parameter space. The peak of the branching ratio resonance emerges when the top-Higgs mass is between $2m_W$ and m_t. The branching ratio $B_r(t \rightarrow cWW)$ can reach 10^{-3} in the narrow range.

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The large value of the top quark mass offers the possibility that it plays a special role in current particle physics. Indeed, the properties of the top quark could reveal information on flavor physics, electroweak symmetry breaking(EWSB) as well as new physics beyond the standard model(SM)[1]. One of these consequences is that the flavor-changing rare top decays which are very small due to the GIM-suppressed in the SM can be used to detect new physics. This fact has lead to a lot of theoretical activity involving the rare top decays within some specific models beyond the SM[2].

The strong top dynamical symmetry breaking models, such as topcolor-assisted technicolor(TC2) models[3] and top see-saw models[4], are attractive because they explain the large top quark mass and provide possible dynamical mechanism for breaking electroweak symmetry. Such type of models generally predict light composite scalars with large Yukawa couplings to the third generation. This induces distinct new flavor mixing phenomena which may be tested at both low and high energies [5, 6]. For example, TC2 theory [3] predicts the existence of the top-pions($\pi_t^{\pm}, \pi_t^0$) and the neutral CP-even state, called top-Higgs h_t^0. These new particles are most directly related to the dynamical symmetry breaking mechanism. Thus, studying the possible signatures of these new particles at high energy colliders will be of special interest.

Ref[5] has pointed out that the Yukawa couplings of the scalars to charm and bottom quarks can be large due to a significant mixing of the top and charm quarks. Furthermore, the neutral scalars(π_t^0 and h_t^0) can couple to a pair of gauge bosons through the top quark triangle loop in an isospion violating way[7]. The main difference between the neutral top-pion π_t^0 and top-Higgs h_t^0 is that h_t^0 can couple to gauge boson pairs WW and ZZ at tree level, which is similarly to that of the SM Higgs H. Thus, the neutral scalars may have significant contributions to the rare top decays $t \to cVV(V = W, g, \gamma$ or $Z)[t \to cWW$ (only for h_t^0), $t \to cgg$, $t \to c\gamma\gamma$ and $t \to cZ\gamma]$.

The top quark mass has been measured [8] by reconstructing the decay products of top pairs produced at the Tevatron. The combined measurement from CDF and D0 is $m_t \doteq 173.4 \pm 5.1$GeV. This implies that the rare top decay $t \longrightarrow cWW$ is allowed. However, this process is occurring near threshold and is highly phase space suppressed.

Within the SM, the decay channel $t \longrightarrow cWW$ is also highly GIM-suppressed ($B_r^{SM}(t \longrightarrow cWW) \approx 10^{-13}$[9]), which can not be observed in the future high energy colliders. So, studying such rare top decay will be very useful to detect the effects of new physics.

In this letter, we first calculate the contributions of the top-Higgs h_t^0 to the rare decay channel $t \longrightarrow cWW$. We find that the peak of the branching ratio resonance emerges when the top-Higgs mass is between $2m_W$ and m_t. For $m_{h_t^0} = 165$ GeV, the value of $B_r(t \longrightarrow cWW)$ is 3×10^{-3} for $\varepsilon = 0.01$ and 5.6×10^{-2} for $\varepsilon = 0.08$. We further estimate the partial widths of the rare top decays $t \to cgg$, $t \to c\gamma\gamma$ and $t \to cZ\gamma$ contributed by the neutral scalars (π_t^0 and h_t^0). The new contributions can enhance the SM partial widths by several orders of magnitude. Even so, it is very difficult to detect the possible signatures of the neutral scalars via these flavor-changing processes.

To solve the phenomenological difficulties of traditional TC theory, TC2 theory [3] was proposed by combing TC interactions with the topcolor interactions for the third generation at the scale of about 1 TeV. In TC2 theory, the TC interactions play a main role in breaking the electroweak symmetry. The ETC interactions give rise to the masses of the ordinary fermions including a very small portion of the top quark mass, namely εm_t with a model dependent parameter $\varepsilon \ll 1$. The topcolor interactions also make small contributions to the EWSB, and give rise to the main part of the top quark mass, $(1-\varepsilon)m_t$. So, for TC2 theory, there is the following relation:

$$\nu_\pi^2 + F_t^2 = \nu_w^2, \tag{1}$$

where ν_π represents the contributions of the TC or other interactions to the EWSB, $F_t \approx 50GeV$ is decay constant of the scalars predicted by TC2 theory, and $\nu_w = \nu/\sqrt{2} \approx 174GeV$. Thus, the majority of the masses of gauge bosons W and Z come from the technifermion condensate.

For TC2 models, the underlying interactions, i.e. topcolor interactions, are non-universal and therefore do not possess a GIM mechanism. When the non-universal interactions are written in the mass eigen-states, it may lead to the flavor changing coupling vertices of the new gauge bosons, such as $Z'tc, Z'\mu e, Z'\mu\tau$. Thus, the new gauge boson Z'

have significant contributions to some lepton flavor changing processes[10]. Furthermore, the neutral scalars predicted by this kind of models have the flavor changing scalar coupling vertices. The coupling of the neutral scalars S (π_t^0 or h_t^0) to the ordinary fermions can be written as[3, 5]:

$$St\bar{t}: \frac{im_t}{\sqrt{2}F_t}\frac{\sqrt{\nu_w^2-F_t^2}}{\nu_w}K_{UR}^{tt}, \quad S\bar{t}c: \frac{im_t}{\sqrt{2}F_t}\frac{\sqrt{\nu_w^2-F_t^2}}{\nu_w}K_{UR}^{tc}. \tag{2}$$

Ref.[5] has shown that the value of K_{UR}^{ij} can be taken as:

$$K_{UR}^{tt}=1-\varepsilon, \quad K_{UR}^{tc}\leq\sqrt{2\varepsilon-\varepsilon^2}. \tag{3}$$

The couplings of the scalars to the bottom quark can be approximately written as :

$$Sb\bar{b}: \frac{i(m_b-m_b^{'})}{\sqrt{2}F_t}\frac{\sqrt{\nu_w^2-F_t^2}}{\nu_w}, \tag{4}$$

where $m_b^{'}$ is the ETC generated part of the bottom-quark mass. According to the idea of TC2 theory, the masses of the first and second generation fermions are also generated by ETC interactions. We have $\varepsilon m_t=\frac{m_c}{m_s}m_b^{'}$ [11]. If we take m_s=0.12GeV and m_c=1.2GeV, then we have $m_b^{'}=0.1\times\varepsilon m_t$.

The couplings of the neutral scalars to gauge boson pairs gg, $\gamma\gamma$ or $Z\gamma$ via the top quark triangle loop are isospin violating. The general form of the effective $S-V_1-V_2$ couplings can be written as [7, 12]:

$$\frac{1}{1+\delta_{V_1V_2}}\frac{\alpha S_{SV_1V_2}}{\pi F_t}S\epsilon_{\mu\nu\alpha\beta}(\partial^\mu V_1^\nu)(\partial^\alpha V_2^\beta), \tag{5}$$

where V_1^ν and V_2^β represent the field operators of the gauge bosons. The anomalous factors $S_{SV_1V_2}$ are model dependent. They have been given in Refs.[6,12].

The neutral top-pion π_t^0 can not couple to gauge boson pairs WW and ZZ at tree level. The couplings of the top-Higgs h_t^0 to the electroweak gauge bosons at tree level are suppressed by the factor F_t/ν_w with respect to that of the SM Higgs. For the top-Higgs h_t^0, we have

$$h_t^0WW: \frac{iF_t}{\nu_w}gm_Wg_{\mu\nu}, \quad h_t^0ZZ: \frac{iF_t}{\nu_w}\frac{gm_Z}{cos\theta_W}g_{\mu\nu}. \tag{6}$$

From above discussion, we can see that the top-Higgs h_t^0 may have significantly contributions to the rare top quark decay channel $t \longrightarrow cWW$. The relative amplitude is:

$$
\begin{aligned}
M(t \longrightarrow cWW) &= \frac{m_t}{\sqrt{2}F_t}\frac{\sqrt{\nu_w^2 - F_t^2}}{\nu_w}K_{UR}^{tc}\frac{F_t g m_W}{\nu_w}\overline{u}(p_c)\gamma_5 u(p_t) \\
& \quad \frac{1}{K^2 - m_{h_t^0}^2 + i m_{h_t^0}\Gamma_{total}}\varepsilon_\mu(k_1,\lambda_1)g^{\mu\nu}\varepsilon_\nu(k_2,\lambda_2),
\end{aligned} \tag{7}
$$

where the four momenta K is given by

$$
K = P_t - P_c = k_1 + k_2. \tag{8}
$$

Where k_i is the four momenta of the gauge boson W. For $150GeV \leq m_{h_t^0} \leq 350GeV$, the total decay width of the top-Higgs h_t^0 can be written as :

$$
\begin{aligned}
\Gamma_{total} &= \Gamma(h_t^0 \longrightarrow b\overline{b}) + \Gamma(h_t^0 \longrightarrow gg) + \Gamma(h_t^0 \longrightarrow \gamma\gamma) \\
&+ \Gamma(h_t^0 \longrightarrow Z\gamma) + \Gamma(h_t^0 \longrightarrow \overline{t}c)(for \quad m_{h_t^0} \geq m_t + m_c) \\
&+ \Gamma(h_t^0 \longrightarrow WW)(for \quad m_{h_t^0} \geq 2m_W) \\
&+ \Gamma(h_t^0 \longrightarrow ZZ)(for \quad m_{h_t^0} \geq 2m_Z).
\end{aligned} \tag{9}
$$

The branching ratio $B_r(t \longrightarrow cWW)$ contributed by the top-Higgs h_t^0 is plotted in Fig.1 as a function of the top-Higgs mass $m_{h_t^0}$ for three values of the parameter ε. In Fig.1 we have assumed that the total top width is dominated by the decay channel $t \longrightarrow Wb$ and taken $\Gamma(t \longrightarrow Wb) = 1.56GeV$[1]. The three-body phase space integral was performed numerically for the parameter values $m_W = 80.4GeV$, $m_t = 175GeV$, $m_c = 1.2GeV$, $\alpha_e = \frac{1}{128}$, $\alpha_s = 0.118$ and $\sin\theta_w = 0.2312$ [13]. From Fig.1 we can see that the peak of the branching ratio $B_r(t \longrightarrow cWW)$ resonance emerges when $m_{h_t^0}$ is between $2m_W$ and m_t. This is consisted with the results obtained in Ref.[14]. For $m_{h_t^0}$=165GeV, the value of the $B_r(t \longrightarrow cWW)$ is 3×10^{-3} for ε=0.01 and 5.6×10^{-2} for ε=0.08. The $B_r(t \longrightarrow cWW)$ decreases rapidly in the regions $m_{h_t^0} < 2m_W$ or $m_{h_t^0} > m_t$. However, for most of the parameter space of the TC2 theory, the branching ratio is several orders of magnitude larger than the $B_r^{SM}(t \longrightarrow cWW)$.

The amplitudes of the rare top decays $t \to cgg$, $t \to c\gamma\gamma$ and $t \to cZ\gamma$ generated by the neutral top-pion π_t^0 can be written as:

$$M(t \to cVV) = \frac{m_t}{\sqrt{2}F_t}\frac{\sqrt{\nu_w^2 - F_t^2}}{\nu_w}K_{UR}^{tc}\frac{\alpha S_{\pi_t^0 V_1 V_2}}{2\pi F_t} \tag{10}$$
$$\overline{u}(P_c)\gamma^5 u(P_t)\frac{1}{K^2 - m_{\pi_t}^2 + im_{\pi_t}\Gamma}(P_{V_1\mu}\epsilon_{V_1\nu} - P_{V_1\nu}\epsilon_{V_1\mu})(P_{V_2}^{\mu}\epsilon_{V_2}^{\nu} - P_{V_2}^{\nu}\epsilon_{V_2}^{\mu}),$$

where Γ is the total decay widths of the neutral top-pion π_t^0.

The partial decay widths of the rare top decay channels $t \to cVV$ are plotted in Fig.2 as functions of the top-pion mass m_{π_t} for $\epsilon = 0.01$. In Fig.2, we have taken the cut that the angle between photons or gluons is larger than 15° and the energy of photons or gluons $E_{\gamma(g)} \geq 20GeV$. From Fig.2 we can see that the partial widths decrease as m_{π_t} increasing in most of the parameter space. If we assume that the part of the top quark mass generated by the topcolor interactions makes up 99% of m_t, then we have $\Gamma(t \to cgg) \sim 10^{-9}GeV$, $\Gamma(t \to c\gamma\gamma) \sim 10^{-10}GeV$ and $\Gamma(t \to cZ\gamma) \sim 10^{-10}GeV$.

Ref.[15] has discussed the rare top decay channel $t \to cH$ in the SM. Their results show that $B_r(t \to cH) \approx 9 \times 10^{-14}$ for $m_H = 100GeV$. The dominant decay modes of the SM Higgs boson are $b\bar{b}$, $\tau\bar{\tau}$ and $c\bar{c}$. The branching ratios $B_r^{SM}(H \to VV)$ are very small: $B_r^{SM}(H \to gg) \approx 5 \times 10^{-2}$, $Br^{SM}(H \to \gamma\gamma) \sim 10^{-3}$ and $B_r^{SM}(H \to Z\gamma) \sim 10^{-4}$[16]. Thus, the $B_r(t \to cVV)$ contributed by the neutral top-pion π_t^0 is larger than that of the SM by several orders of magnitude.

The contributions of h_t^0 to the rare top decays $t \to cVV$($V = g$, γ or Z) are similar to that of π_t^0. Certainly, h_t^0 can couple to gauge boson pair WW and can give contributions to the rare top decays $t \to c\gamma\gamma$ and $t \to cZ\gamma$ via W loops. This may enhance the branching ratios $B_r(t \to c\gamma\gamma)$ and $B_r(t \to cZ\gamma)$ relative to that of π_t^0. However, the coupling h_t^0WW is suppressed with respect to the case of the SM Higgs boson H by a factor $\frac{F_t}{\nu_w}$. Thus the enhancement is very small. We can neglect the contributions of W loops to the rare top decays $t \to c\gamma\gamma$ and $t \to cZ\gamma$. The decay widths of the decays $t \to cVV$ ($V = g$, γ or Z) given by the top-Higgs h_t^0 approximately equal to that of the neutral top-pion π_t^0.

To assess the discovery reach of the rare top quark decays in the future high energy colliders, Ref.[17] has roughly estimated the following sensitivities for $100fb^{-1}$ of integrated

luminosity :

$$LHC : B_r(t \longrightarrow cX) \geq 5 \times 10^{-5} \tag{11}$$

$$LC : B_r(t \longrightarrow cX) \geq 5 \times 10^{-4} \tag{12}$$

$$TEV33 : B_r(t \longrightarrow cX) \geq 5 \times 10^{-3} \tag{13}$$

Thus, the effects of h_t^0 on the rare top decay $t \longrightarrow cWW$ can be detected in the future high energy colliders. If it is not this case, we can conclude that the mass of the top-Higgs h_t^0 must be larger than 180GeV.

The scalars predicted by the TC2 theory have large Yukawa couplings to the third family fermions and induce the new flavor changing scalar couplings including the $t - c$ transitions for the neutral scalars. Thus, the neutral scalars have significant contributions to the rare top decay channels $t \rightarrow cVV$. If the mass of the top-Higgs lies in the narrow range $160GeV \leq m_{h_t^0} \leq 180GeV$, the rare top decay $t \rightarrow cWW$ may be used to detect the signatures of the top-Higgs h_t^0. For the neutral top-pion π_t^0, we have to use other processes to detect its possible signatures.

Figure captions

Fig.1: The branching ratio $B_r(t \to cWW)$ as a function of the top-Higgs mass m_{h_t} for the parameter $\epsilon = 0.01$ (solid line), 0.05(dotted line) and 0.08(dashed line).

Fig.2: The partial decay widths $\Gamma(t \to cVV)$ versus the mass m_{π_t} for $\epsilon = 0.01$.

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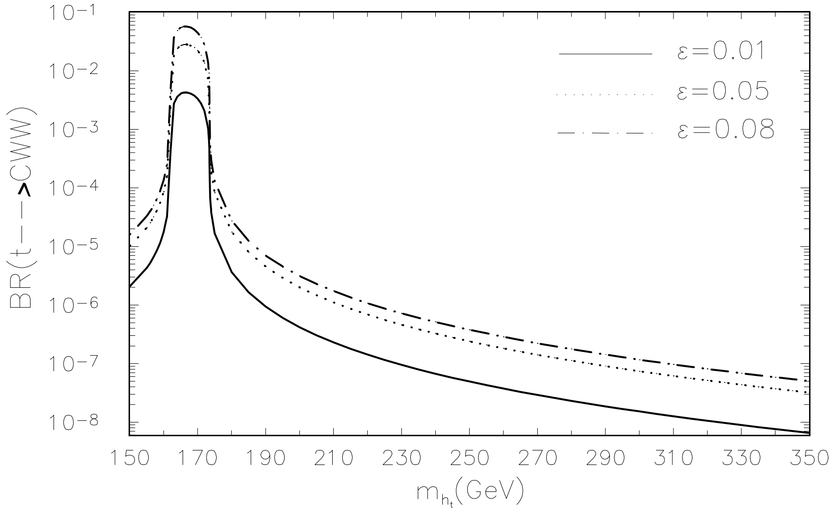
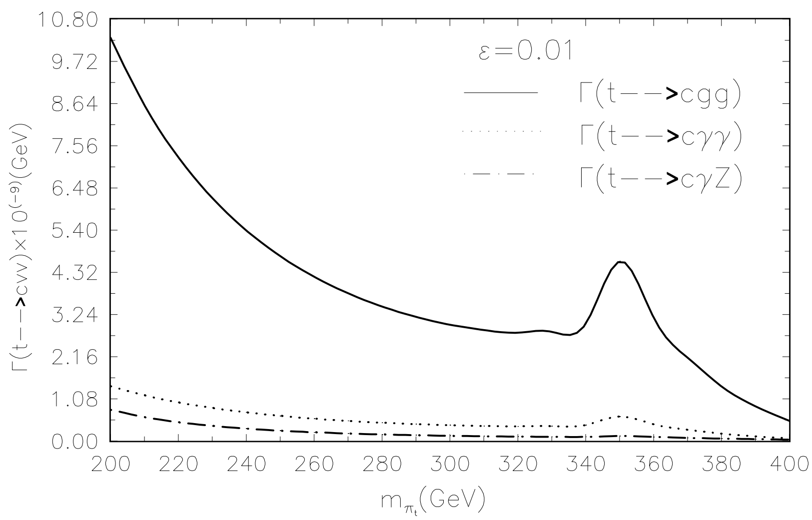


ε=0.01
ε=0.05
ε=0.08
BR(t-->CWW)
m_{h_t}(GeV)

Fig.1



ε=0.01
Γ(t-->cgg)
Γ(t-->cγγ)
Γ(t-->cγZ)
Γ(t-->cvv)×10^(-9)(GeV)
m_{π_t}(GeV)

Fig.2